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Final Report for
“Student Support for Quantum Computation with Superconducting Quantum Devices”
Grant number DAAD19-01-1-0624 and proposal number P-42633-0PH-QCO-01101-1

Terry P. Orlando
Massachusetts Institute of Technology

Report for June 1, 2001 – December 31, 2004

Contents:

1. Abstract

The research done by the graduate students on this grant focus on two topics: predominately, the focus was on the measurements of a persistent-current qubit driven by an on-chip radiation source, and secondarily on the fabrication of qubits for a fast turn around time.

For the first topic the student preformed experiments of the monolithic integration of an on-chip radiation source with a persistent-current (PC) qubit and dc SQUID measurement device. The devices were fabricated at MIT Lincoln Laboratory in a Nb/Al/AlOx/Nb trilayer process. The two PC qubit states were detected by measuring the switching current of an underdamped dc SQUID magnetometer inductively coupled to the qubit. The radiation source comprised an overdamped dc SQUID operating in the voltage state and inductively coupled to the qubit and measurement SQUID through a low-Q RLC filter. The oscillator was designed to have tunable amplitude and frequency to satisfy the requirements for coherent quantum manipulation of a superconducting PC qubit. Measurements were made in the millikelvin regime and the effects of the oscillator noise on the state of the qubit were obtained. For the second topic, work was done for implementing a fabrication process for superconducting qubits with a turn-around time of the order of a few weeks.

2. List of Manuscripts

1. K. Segall, D. S. Crankshaw, D. Nakada, B. Singh, J. Lee, T. P. Orlando, K.K. Berggren, N. Markovic, and M. Tinkham, " Experimental characterization of the two current states in a Nb persistent-current qubit," *IEEE Transactions on Applied Superconductivity* **13**, 1009-1012, 2003.
2. Y. Yu, D. Nakada, J. C. Lee, B. Singh, D. S. Crankshaw, T. P. Orlando, K. K. Berggren and W. D. Oliver, "Energy relaxation time between macroscopic quantum levels in a superconducting persistent-current qubit," *Phys.l Rev. Lett.s*, vol. **92,** no. 3, pp. 117904, Mar. 2004.
3. Jonathan L. Habif, Bhuwan Singh, Donald S. Crankshaw, Karl K. Berggren and Terry P. Orlando, "Measurements of a Persistent-Current Qubit Driven by an On-Chip Radiation Source" to be published in the *IEEE Transactions on Applied Superconductivity* in 2004. Paper was presented at the 2004 Applied Superconductivity Conference in Jacksonville, Florida.

3. Scientific Personnel

Graduate student Bhuwan Singh was supported by this grant until May 2004. From May to July, Bryan Cord was supported on this grant, Bryan is a doctoral student in the Department of Electrical Enginering and Computer Science at MIT. The first topic reported here is the work of Bhuwan Singh, and the second, which is just beginning, is the work of Bryan Cord who will continue on a QuCAR.

4. Report on Inventions

No patents have been filed.

5. Scientific Progress

A. On-chip Oscillator results

Both the qubit and the dc-SQUID oscillator were characterized according to the fabricated parameters, and measurements were made of the qubit when operated with and without the accompaniment of a microwave signal from the oscillator. Data collected at 350 mK indicate both increased thermalization due to broad frequency noise coupled from the oscillator as well as signatures of stimulation between quantized energy levels of the system.

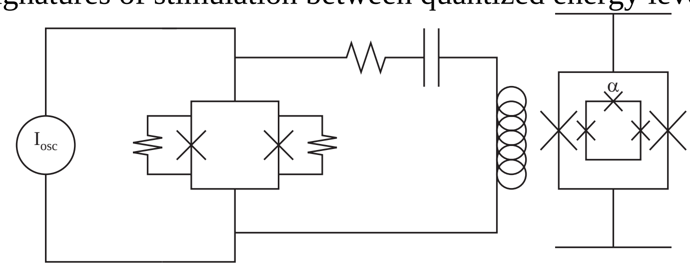

Fig. 1 A schematic representation of the on-chip oscillator circuit with a bandpass filter, coupled inductively to the pc-qubit and measurement SQUID. The entire circuit was fabricated monolithically in a superconducting foundry with Jc ~ 5.72μA/μm^2.

The two discrete units of the complete circuit are the persistent-current (pc) qubit inductively coupled with a dc-SQUID magnetometer for readout of the qubit, and the highly damped dc-SQUID oscillator connected to a bandpass filter and inductively coupled to the pc-qubit. The circuit is shown schematically in Fig 1.

The ratio of the areas of the dc-SQUID and the pc-qubit were designed such that a qubit undergoes a transition for each 1.5 lobes of the SQUID modulation curve. The qubit signal is shown in Fig. 2 with the dc-SQUID modulation curve subtracted. The qubit modulated the dc-SQUID critical current by 100 – 300 nA, depending on its location along the SQUID modulation curve.

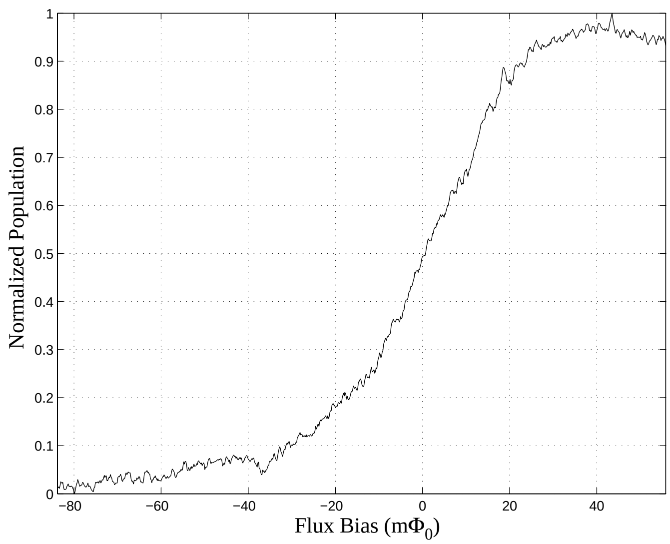

Fig. 2 A qubit step with the SQUID modulation curve subtracted. As the flux through the pc-qubit is swept from below to above one half flux quantum the system switches from being localized in the ‘0’ state to the ‘1’ state.

The structure in the qubit step in Fig. 2 indicates evidence of incoherent tunneling between energy levels as the measurement SQUID is ramped. Rather than a smooth transition between the two states of the qubit as the flux is swept through $\Phi_0/2$, plateaus appear in the transition. This structure is due to excitations occurring at energy level anti-crossings caused by the mutual inductance between measurement SQUID and pc-qubit as the current to the SQUID is swept to make a measurement. The location of these anti-crossings can be mapped to an energy level bandstructure diagram. By fitting the bandstructure to the location of these plateaus the size of the qubit junctions can be determined. Assuming that the junction undercut is equal for all three junctions in the pc-qubit loop, the sizes of the junctions were determined to be 0.4 x 0.4 μm for the smaller junction and 0.5 x 0.5 μm for the larger two, yielding $\alpha = 0.64$.
The dc-SQUID oscillator serves as a microwave source with tunable frequency and was designed to be highly overdamped (β_c<<1) to allow for precise frequency adjustments of the device.

The tank circuit coupled to the dc-SQUID oscillator serves as a bandpass filter suppressing unwanted harmonics produced by the Josephson oscillator which is highly nonlinear when operating at frequencies well below the plasma frequency (ω_p). The filter resistor (R_f), capacitor (C_f) and inductor (L_f) were designed to be 0.73Ω, 4.6 pF and 75 pH, respectively. The bandpass region for the oscillator-filter system occurred between approximately 7 to 11 GHz.

The analysis of the qubit-oscillator interaction entailed examining the standard deviation of the data obtained when measuring the qubit step at each oscillator bias, and is shown in Fig. 3. The data indicate phenomena arising from the qubit – oscillator interaction that is dependent on the current bias to the oscillator and therefore dependent on the oscillator frequency. As the current bias to the oscillator is increased a peak arises in the standard

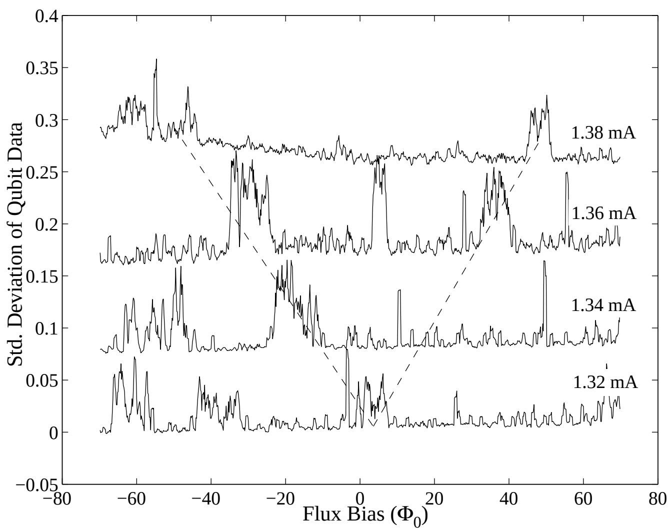

Fig. 3 This contour plots the standard deviation of the data from the qubit step as a function of I_{osc}. Horizontal slices are the data from the individual qubit steps. The data shows an increase in the standard deviation that moves away from the center of the step with increasing oscillator bias. When I_{osc} reaches 1.38 mA the signal from the measurement SQUID is suppressed by the oscillator.

deviation data and moves away from the center of the qubit step as the oscillator frequency is increased. As Iosc is increased above ~1.37 mA the critical current of the measurement SQUID is suppressed along the entire region of the qubit step and the standard deviation increases accordingly, though in Fig. 3, the peak in the standard deviation is still apparent and maintains the trend followed in the rest of the data.

The data obtained from oscillator – qubit interaction indicate weak spectroscopic evidence and increased thermalization of the pc-qubit. Though operation at dilution refrigerator temperatures will reveal more striking quantum signatures, it is maintained that this type of on-chip oscillator represents the most rudimentary of the Josephson oscillator family, and was chosen for robust operation as opposed to optimal performance.

The oscillation stability of a highly damped Josephson junction has been thoroughly examined. The expression for the linewidth of a Josephson oscillator using the RSJ model is,

$$\Gamma = \pi\left(R_d^2 / R_N\right)\left(2e/\hbar\right)^2 k_B T\ , \qquad (2)$$

where k_B is Boltzmann's constant and T is temperature. The dynamic resistance R_d is calculated by differentiating (1) with respect to I_{osc} and evaluating for ($I_{osc} > I_c^{osc}$). Using (2) and the parameters for our fabricated oscillator at 350 mK the oscillator linewidth is calculated to be 100 MHz at 10 GHz, a frequency typical for superconducting qubit operations. A linewidth of this order of magnitude is far larger than that from a room temperature microwave source and insufficient for performing quantum coherent manipulations of a superconducting qubit. Experimental measurements of simple Josephson oscillators, similar to our, have been made and the measured linewidths agree well with (2).

A great deal of effort has been focused on narrowing the linewidth and phase stability of

Josephson oscillators. Various types of Josephson oscillators exist, from long Josephson Junction resonant soliton and flux-flow oscillators to digital RSFQ ring oscillators, that can provide linewidths in the kHz range for performing qubit operations.

Integrating already mature superconducting classical electronics with superconducting quantum bits will capitalize on the relative ease of scalability of superconducting quantum computer architectures over other implementations. Experiments like the one reported here must be increased in complexity and characterized in order to find efficient means for on-chip quantum control of superconducting qubits.

B. Short Loop Superconducting Fabrication Process

The work of Bryan Cord (who was funded only for a few months at the end of this grant) focused on his implementing a fabrication process for superconducting qubits with a turn-around time of the order of a few weeks. Such a new short-loop process for the fabrication of Nb-on-Si superconductive quantum circuits was developed in collaboration with MIT Lincoln Laboratory. Three major steps are involved in this: characterizing the process, fabricating and testing devices, and modifying the process to improve yield and results. This short-loop process will enhance the present program by allowing quicker testing of superconducting qubit designs.

The key features enabling rapid turnaround are: (1) the use of a self-aligned anodization step to form the only insulating layer in the process; (2) the use of only two wiring layers; (3) the absence of planarization and resistors; and (4) elimination of much of the in-process testing and metrology. The proposed process was inspired by our observation that NbO_x provides an entirely adequate insulator for small-scales of integration.This short-loop process will enhance the present program by allowing quicker testing of superconducting qubit designs. Bryan finished his master's thesis on this project and finished working on the project at Lincoln Laboratory at the end of this grant in July. He is now working on the fabrication of superconducting qubits on campus with me and Professor Karl Berggren and he will be funded by a similar student support grant.